AFRL-OSR-VA-TR-2013-0591

TOPOLOGICAL QUANTUM INFORMATION PROCESSING MEDIATED VIA HYBRID TOPOGICAL INSULAT OR STRUCTURES

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03/28/2014
Final Report

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Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTD
Arlington, Virginia 22203
Air Force Materiel Command

Final Progress Report

Title: Topological Quantum Information Processing Mediated Via Hybrid Topological Insulator Structures

Grant/Contract Number: FA9550-10-0459

Program Manager: Harold Weinstock

Abstract:

Spin has long been known to have the potential to perform universal quantum computation. To realize quantum computation with spins one needs an extraordinary amount of control over the spins so we can set, manipulate, and read out the various processes required in information processing. This is a daunting task as these processes are not immune from decoherence. While one can manipulate single spins with high-fidelity and long coherence times, there is no clear path to move from single spin manipulation to many spins. Recent advances have revealed a new type of information processing, topological quantum computation, which is immune from environment related decoherence. Topological information processing relies on the manipulation of anyons, particles which obey non-Abelian statistics. The simplest of these particles, Majorana fermions, are believed to exist as excitations in exotic materials under extreme conditions. Additionally, Majorana fermions have been proposed to exist in a new class of materials commonly referred to as topological insulators coupled with superconducting contacts under much less extreme conditions. In this work, we propose to theoretically investigate the formation, manipulation, entanglement and detection of Majorana fermions in diamond-topological insulator-superconductor heterojunctions. Furthermore, we propose to further investigate the relationship between superconducting elements and 2D and 3D topological insulators. The tasks we outline in this proposal will be undertaken using a variety of analytical tools to provide insight into the system behavior at the theoretical limits and numerical techniques to yield results in experimentally realistic conditions. The goal is to make significant and measurable advances towards transformative information processing technologies that have the potential to vastly increase operational capabilities of multiple Air Force applications. As a corollary, we desired to provide theoretical support and guidance to David Awshcalom's group at University of California-Santa Barbara and David Goldhaber-Gordon's group at Stanford University.

1. Understanding Topological Insulators:

Topological insulators (TI) are a new class of materials that have significant potential as a vehicle for new device technologies. Each TI may be characterized by unique physical properties—such as robust surface states and unusual electromagnetic coupling—cannot be perturbed, due to the presence of underlying symmetries naturally present in these materials. The unique physical properties of TIs can be used for information processing while consuming less power and having fewer dimensional limitations than the MOSFET. The goal is to make significant and measurable advances towards information processing technologies that have the potential to vastly increase operational capabilities of multiple applications by understanding the stability and properties of these unique topological states. Currently, the most readily available topological insulator material is Bi_2Se_3, which has a linear band crossing that is protected by time-reversal symmetry. While the material itself is plentiful the quality of the material makes the identification of the topological nature of this material quite difficult experimentally via probes beyond angle resolved photoemission spectroscopy (ARPES).

My group has studied several different aspects of TI with emphasis on performing theory that may easily be transferred into experiments. To this end, we have studied methods for detecting topological transport using quantum degenerate gases[1], classifying topological phase transitions[2], exotic superconducting states[3], spin transport properties[4], and the possibility of finding collective condensate phases on the surface of 3D TI[5].

Relevant Publications:

[1] Brian Dellabetta, Taylor L. Hughes, Matthew J. Gilbert, and Benjamin L. Lev, "Imaging Topologically Protected Transport with Quantum Degenerate Gases," *Physical Review B* **85** 205422 (2012).

[2] Matthew J. Gilbert, B. Andrei Bernevig, and Taylor L. Hughes, "Signatures of Phase Transitions in the Disordered Quantum Spin Hall State from the Entanglement Spectrum," *Physical Review B: Rapid Communications* **86**, 041401 (2012).

[3] Qinglei Meng, Taylor L. Hughes, Matthew J. Gilbert and S. Vishveshwara, "Gate Controlled Spin Density Wave and Chiral FFLO Superconducting Phases in Interacting Quantum Spin Hall Edge States," *Physical Review B* **86**, 155110 (2012).

[4] Qinglei Meng, Vasudha Shivamoggi, Taylor L. Hughes, Matthew J. Gilbert and S. Vishveshwara, "Fractional Spin Josephson Effect and Electrically Controlled Magnetization in Quantum Spin Hall Edges," *Physical Review B* **86**, 165110 (2012).

[5] Youngseok Kim, E. M. Hankiewicz, and Matthew J. Gilbert, "Topological Exciton Superfluids in Three Dimensions," *Physical Review B* **86**, 184504 (2012).

2. Interactions between Superconductors and Topological Insulators

Recent advances have revealed a new type of information processing, topological quantum computation, which is immune from environment-related errors and promises to vastly outperform traditional CMOS based logic. Topological information processing relies on the manipulation of anyons, particles that are interesting in the sense that they are neither fermions, like electrons, nor are they bosons, like photons. The simplest of these particles, Majorana fermions, are believed to exist as excitations in exotic materials under extreme conditions. Fortunately, Majorana fermions have been proposed to exist in a new class of materials commonly referred to as topological insulators (TI) coupled with superconducting contacts under much less extreme conditions. TI are a new class of materials that have significant potential as a vehicle for new device technologies. Each TI may be characterized by unique physical properties—such as robust surface states and unusual electromagnetic coupling—cannot be perturbed, due to the presence of underlying symmetries naturally present in these materials. The unique physical properties of TIs can be used for information processing while consuming less power and having fewer dimensional limitations than the MOSFET. The goal is to make significant and measurable advances towards information processing technologies that have the potential to vastly increase operational capabilities of multiple applications by understanding the stability and properties of these unique topological states. These advances are directly applicable to technologies such as unmanned aerial vehicles where the vastly increased computational capability at significantly decreased energy would provide extended range at reduced weight allowing for the inclusion of more operational systems.

My group has taken a broad approach to understanding not only topological quantum computation, but also to understanding time-reversal invariant topological insulators. We have made contributions in the area of vortex lines[6] and lattices[7] in TI – superconductor heterostructures. Some of our most impactful work in this area has come through collaborations with experimental groups at UIUC and Princeton University. With these groups, we have explored topological Josephson junctions[8] and the penetration of superconductivity into TI[9] seeking not only signatures of Majorana fermions but also exploring the future use of the unique properties of this condensed matter system to probe the properties of dark matter and supersymmetry. Furthermore, we have also explored the appearance of Majorana states in emergent topological crystalline insulators[10].

Relevant Publications:

[6] Ching-Kai Chiu, Matthew J. Gilbert and Taylor L. Hughes,"Vortex Lines in Topological Insulator - Superconductor Heterostructures," Physical Review B 84, 144507 (2011).

[7] Hsiang-Hsuan Hung, Pouyan Ghaemi, Taylor L. Hughes, and Matthew J. Gilbert, "Vortex Lattices in the Superconducting Phases of Doped Topological Insulators and Heterostructures," *Physical Review B* **87**, 035401 (2013).

[8] Sungjae Cho, Brian Dellabetta, Alina Yang, John Schneeloch, Zhijun Xu, Tonica Valla, Genda Gu, Matthew J. Gilbert and Nadya Mason, "Symmetry Protected Josephson Supercurrents in Three-Dimensional Topological Insulators," *Nature Communications* **4**, 1689 (2013).

[9] Su–Yang Xu, Nasser Alidoust, Ilya Beloposki, Anthony Richardella, Chang Liu, Madbab Neupane, Song–Hsun Huang, Brian Dellabetta, Alexei Fedorov, Wenqing Dai, Qi Li, Matthew J. Gilbert, F. C. Chou, Nitin Samarth, and M. Z. Hasan, "Momentum Space Cooper Pairing in a Helical Dirac Electron Gas," *Submitted to Science.*

[10] Chen Fang, Matthew J. Gilbert, and B. Andrei Bernevig, "New Class of Topological Superconductors Protected by Magnetic Point Group Symmetries," *ArXiv:1308.2424* (2013). *Submitted to Physical Review Letters*.

3. Emergent Topological Materials

To understand materials properties, we have relied upon band structure theory for more than one hundred years. Our solid understanding of band theory has enabled us to engineer the properties of quantum wells, junctions, and transistors with a high degree of accuracy. As such, it is truly remarkable that more than a century of research has missed the most interesting features of band theory: the possibility of having non-trivial topological band structures. In the past few years, it has been shown that certain insulators support surface (in 3D materials) or edge states (in 2D materials) that cross the bulk band gap and are localized on the surface or edge of the sample. Speaking more generally, topological phenomena may be classified by the symmetries that the preserve. These symmetries are not limited to simply charge-conjugation, chiral, or time-reversal. In solids, the lattice or point group symmetries (PGS) are universal and, therefore, may encompass a much larger group of topological materials including magnetically ordered materials and superconducting materials. These materials promise to provide a fascinating new range of physical phenomena that may be applied to creating new and fundamentally different types of low-power information processing.

My group has become one of the leaders in the classification of: PGS topological insulators[11 12] and semimetals[13], TI with commensurate antiferromagnetic ordering[14], the phase transitions within non-interacting PGS materials[15], new superconductors with exotic properties[16-17] and extending the work to include power-efficient device concepts[18].

Relevant Publications:

[11] Chen Fang, Matthew J. Gilbert, Su-Yang Xu, B. Andrei Bernevig and M. Z. Hasan, "Surface State Quasiparticle Interference in Crystalline Topological Insulators," *Physical Review B* **88**, 125141 (2013).

[12] Chen Fang, Matthew J. Gilbert and B. Andrei Bernevig, "Bulk Topological Invariants in Noninteracting Point Group Symmetric Insulators," *Physical Review B* **86**, 115112 (2012).

[13] Chen Fang, Matthew J. Gilbert, Xi Dai, and B. Andrei Bernevig, "Multi-Weyl Topological Metals Stabilized by Point Group Symmetry," *Physical Review Letters* **108**, 266802 (2012).

[14] Chen Fang, Matthew J. Gilbert, and B. Andrei Bernevig, "Topological Insulators with Commensurate Antiferromagnetism," *Physical Review B* **88**, 085406 (2013).

[15] Chen Fang, Matthew J. Gilbert and B. Andrei Bernevig, "Entanglement Spectrum Classification of Cn-invariant Noninteracting Topological Insulators in Two Dimensions," *Physical Review B* **87**, 035119 (2013).

[16] Chen Fang, B. Andrei Bernevig, and Matthew J. Gilbert, "Tri-Dirac Topological Surface Modes in Topological Superconductors and Possible Realization in Superconducting Heusler Alloys," *Submitted to Physical Review Letters* (2013)

[17] Vasudha Shivamoggi and Matthew J. Gilbert, "Weyl Phases in Point Group Symmetric Superconductors," *Physical Review B* **88**, 134504 (2013).

[18] Chen Fang, Matthew J. Gilbert, and B. Andrei Bernevig, "Large Chern Number Quantum Anomalous Hall Effect in Thin-Film Topological Crystalline Insulators," *ArXiv:1306.0888* (2013). *Submitted to Physical Review Letters*.